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Photographic Method for Visibility Monitoring

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Photographic Method for Visibility Monitoring

L. Willard Richards,* Mark Stoelting, and Robert G. M. Hammarstrand

Sonoma Technology, Inc., 5510 Skylane Boulevard, Santa Rosa, California 95403

■ A visibility monitoring method is described in which photographs are taken at two distances from a scene and the data are reduced to determine the atmospheric transmittance and path radiance for the sight path between the two cameras. Data from the magenta-forming layer of color slide film are used to determine the transmittance and path radiance for green light, and these results are compared with transmittance data for the same sight path measured by teleradiometers and by a transmissometer. A film calibration method that makes it possible to determine radiances from film densities is described. It is recommended that the radiance calibration data and time of the photograph be recorded on each frame to minimize the need for special film handling and for auxiliary data records.

Introduction

Haze and reduced visibility are the effects of air pollution most noticed by the general public and are often thought of by the public as a measure of air quality. The adverse effects of air pollution on the clarity of the air are especially undesirable in remote wilderness areas and in the National Parks, where the scenic vistas are an important part of the visitor's experience. The U.S. Congress sought in the 1977 Amendments to the Clean Air Act to preserve visibility and set as a national goal "the prevention of any future and remedying of any existing impairment of visibility in any mandatory Class I Federal area which impairment results from manmade air pollution". To obtain technical data to learn the origins of visibility reducing hazes and to monitor progress toward achieving this goal, it is necessary to measure the optical properties of the atmosphere that relate to visibility. It is desirable to have a simple, reliable, cost-effective monitoring method that is practical for use even in remote areas.

In recent years, most visibility monitoring in remote areas has been done by the measurement of the contrast of distant terrain features against the horizon sky (*1–3*). An analysis of pairs of measurements taken close to each other has shown that this measurement method gives results that show considerable scatter, even when the sky is relatively free of clouds (*4*). This outcome can easily be explained by the variable illumination of the target and the sight path caused by many factors, including the variations in the reflectance of the ground (*5*). Because of the uncertainties in transmittances calculated from contrast measurements, there is a need for better monitoring methods.

To fill this need, the National Park Service sponsored the development of a transmissometer. The resulting instrument (*6*) requires a significant capital investment and does not provide data for the path radiance. It is shown below that this optical parameter plays an important role in controlling the ability to see through the atmosphere.

Photographic methods have long been used for visibility monitoring (*7–9*). It has been shown that contrasts can be determined from color slides (*10, 11*), and contrast determinations from color slides (*12*) are now being used in a large visibility study (*13*). Photographic methods have the advantage that the equipment is inexpensive to purchase and to automate. There is the additional side benefit that the photographic images provide a subjective record of the visibility conditions at the time of each measurement.

Photographic visibility monitoring methods in current use measure the contrast of distant terrain features against the horizon sky (*12*). It is appealing to determine contrasts from photographs because the necessary calibration procedures are relatively simple (*8, 9*). However, the demonstration by White and Macias (*4*) of the unreliability of transmittance data derived from instrumental measurements of contrast, which are of higher quality than can be obtained from photographic measurements, shows that the photographic data derived from contrast measurements must also be subject to significant uncertainties. The photographic monitoring method described here is free of the approximations typically made (*1*) in the reduction of contrast data.

Theory

When an observer gazes on a scene, light from the viewed target travels through the atmosphere to the eye. The straight line from a target being viewed to the observer's eye is a sight path. The radiance of a ray of light on this sight path is equal to the rate of energy transfer through an area perpendicular to the ray divided by the product of the area, the solid angle of view, and the wavelength range. (Metric units for radiance are W m^{-2} sr^{-1} μm^{-1}.)

The initial radiance I_0 is the radiance measured at some point (which may be near the target) that is the initial point on the sight path. The apparent radiance I is the radiance entering the eye or measurement instrument a distance x farther away from the target than where the initial radiance is measured. The transmittance T of the sight path is equal to the fraction of the initial radiance that reaches the location where the apparent radiance is measured. Therefore, the transmitted radiance is I_0T.

Some of the apparent radiance is due to light that is first scattered into the sight path by the atmosphere between the two measurement locations and then transmitted to the measurement instrument farther from the target. This light, which is caused by the illumination of the atmosphere in the sight path, is the path radiance I_p.

The apparent radiance is always equal to the sum of the transmitted radiance I_0T and the path radiance:

$$I = I_0T + I_p \quad (1)$$

Thus, light entering the eye from a sight path to a distant object comes from two sources: one source is the object itself, which contributes the transmitted radiance, and the other is the intervening atmosphere, which contributes the path radiance.

The transmittance, path radiance, and initial radiances of a sight path are necessary and sufficient to characterize the visibility for that sight path. Therefore, the ability to measure these quantities is of great practical interest. That they are sufficient can be shown by using them in eq 1 to calculate the apparent radiance I corresponding to any initial radiance I_0. The apparent radiances can then be used to calculate parameters related to human vision, such as contrast and modulation. Such calculations are valid for the sight path, times, and wavelengths of the moni-

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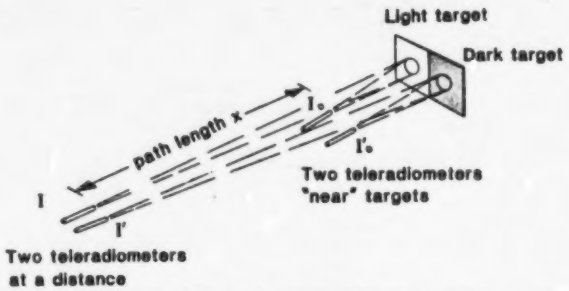

Figure 1. Schematic diagram of a method for measuring the transmittance and path radiance of a sight path.

toring data. (Very intense laser beams that physically modify the atmosphere in the sight path by heating the air are an exception.) The optical properties of the atmosphere are typically a strong function of wavelength, so it is highly desirable to use measurement methods that respond to relatively narrow ranges of wavelengths.

It is common in visibility studies to measure only the transmittance. The reasons for this are that light extinction is independent of the illumination of the sight path and is closely linked to air quality by relationships that are well understood but difficult to apply in practice (*14*, *15*), and transmittance is affected only by extinction.

However, it is important to also measure the path radiance because of its key role in determining the ability to see along a sight path. Computer-generated photographs have been used to show that attenuated transmittance *by itself* does not cause a sensation of reduced visibility (*16*). Furthermore, it is a good generalization that when a scene is far enough away that visibility is of concern, most of the apparent radiance is due to the path radiance (*5*). For example, when the atmosphere is very clear so that the visual range is 200 km, the path radiance will contribute more to the apparent radiance than will the transmitted radiance for a sight path to a wooded hillside only 9 km away. In this example, it was assumed that the initial radiance of the wooded hillside was 20% of the radiance of the horizon sky.

A satisfactory method for measuring the transmittance and path radiance of a sight path in the atmosphere was used by Haecker more than 80 years ago (*17*). The geometry of the experiment is schematically shown in Figure 1. A light and dark panel are placed side-by-side, and four teleradiometers are used to measure the apparent radiances of the panels at two distances along the same sight path. Equation 1 can be used for the sight path to the light target, and a similar equation,

$$I' = I_0'T + I_p \tag{2}$$

used for the sight path to the dark target. The I_0 and I_0' in these equations refer to initial radiances at the measurement location (camera or teleradiometer location) nearer the target. It is assumed in these equations that the sight paths to the light and dark targets are close enough together that the transmittance and path radiance are the same for each sight path. Subtracting eq 2 from eq 1 gives

$$I - I' = (I_0 - I_0')T \tag{3}$$

This equation shows that radiance differences are attenuated by atmospheric extinction in just the same way as the individual radiances. However, the radiance differences are not influenced by the illumination of the atmosphere in the sight path. Any light scattered into the sight path affects the apparent radiances of the adjacent light and dark targets equally and has no effect on the difference in radiances. It is not necessary that the targets be uniform in either space or time. Natural targets of uneven reflectance can be used as long as the near and far teleradiometers view the same areas from the same angle and there is a measurable difference in the radiance of the two target areas. If the teleradiometer readings are averaged for a period of time, the illumination of the targets need not be constant during that time as long as the averages are determined for the same time intervals at each location.

The radiances in eq 3 can be multiplied by an arbitrary constant without affecting the value of the transmittance calculated from them. Therefore, for the determination of transmittances, it is only necessary that the radiance scales used at each end of the sight path be cross calibrated. Absolute calibration of the radiance scale allows reporting path radiances on an absolute basis.

The theory behind this measurement method has long been recognized as being fundamentally sound (*1*, *18*, *19*). The version of the method in which teleradiometers are used to measure radiances has recently been used in the field (*20*, *21*) and has been recommended by L.W.R. as a reference method for visibility monitoring (*5*). The photographic method used here is an extension of Haecker's ideas.

Experimental Section

The photographic visibility monitoring method was evaluated in preliminary experiments near Santa Rosa, CA. The camera near the photographed scene was on the north ridge of Taylor Mountain and was focused on Bennett Mountain, which was at a distance of ~3.2 km. The camera far from the scene was at the Santa Rosa Air Center 7.1 km farther away from Bennett Mountain. The sight path from the far camera site passed directly over and close to the near camera site and viewed a portion of Bennett Mountain that had large patches of light-colored dry grass and dark oak trees. The azimuth of the direction of view was 88° east of true north. Gray scales were placed in the field of view of each camera. They were made with matte gray paper or black velour and had six panels with diffuse reflectances of 1.4, 9.0, 19.8, 36.2, 59.1, and 90%.

The camera far from the scene used a Tokina 800-mm fixed focal length lens and the near camera used a Tokina 35–135-mm zoom lens. Both lenses had haze filters that absorbed ultraviolet light. Ideally, the focal lengths of the lenses are inversely proportional to the distances to the scene so that the images are the same size, so the zoom lens was set at a focal length of 135 mm to be as close to the ideal as possible. An MRI Model 3010 manual teleradiometer was set up near each camera and used to take readings of the gray scale panel with a reflectance of 36.2% at the same time each photograph was taken. Kodachrome 64 slide film was used, and the exposures were selected to use the midportion of the film latitude. Exposures were also made at twice and half the ideal exposure. Photographs were taken on successive days that varied from fairly clear to hazy. All photographs were taken by operators who talked over citizen's band radios to synchronize times.

Data were recorded by two other measurement methods. One was the rotating target method described by Richards and Stoelting (*20*, *21*). This instrument is a transmissometer that uses a 4-ft-diameter diffuse reflector as a light source. The reflector consists of a rotating disk behind a mask with pie-shaped cutouts, and the disk is painted so that the portions that can be seen through the cutouts alternate between all white and all black. The amplitude of the triangular wave light signal was measured close to the rotating target and at a distance of 7.1 km. The

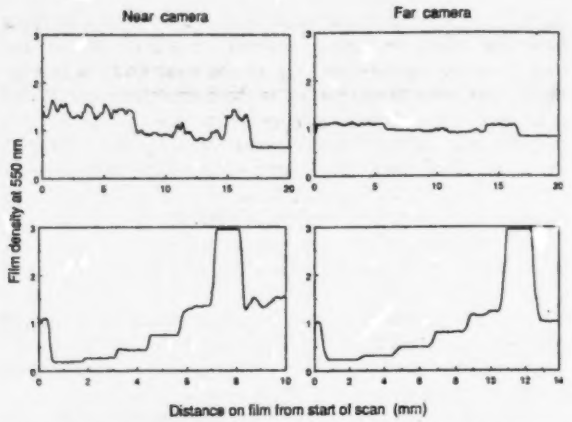

Figure 2. Film density scans from slides taken at the same time at the near and far sites. The top panel is a vertical scan through the scene to the sky, and the bottom panel is a scan of the calibration scale.

transmittance of the sight path is equal to a calibration constant times the signal measured at a distance divided by the signal measured near the rotating target. The sight path was essentially the same as the one used for the photographic and teleradiometer measurements.

Data were also recorded with the MRI Model 3010 manual teleradiometers by using measurement geometry described by Haecker (*17*) and shown in Figure 1. Radiance readings for a light-colored grassy area and a dark-colored area covered with live oak trees were taken at the near and far sites by the camera operators, and the differences in the radiances were calculated. The transmittance was calculated by using eq 3.

The photographic film was submitted to Kodak for normal processing, including standard 2 × 2 in. cardboard mounts. The slides selected for data reduction were sent to Air Resource Specialists, where film densities were measured along scan lines with the equipment and procedures described by Johnson et al. (*12*). All scans were made with green (550-nm) light. Two scans were made on each slide, one the length of the calibration scale and the other vertically through the scene and into the sky. All scans of the scene passed through the image of a tree that could be easily identified in each photograph. The film density data were returned as plots and data tables on floppy disks.

Data Reduction

The photographic data were reduced by procedures adequate for the demonstration of a new measurement method. Many steps were performed by hand calculations that could be automated for reducing larger quantities of data.

Figure 2 shows the results of the film density scans for a pair of photographs taken at the same time. All film density data for the calibration gray scales were imported into a spreadsheet program on a personal computer and the mean values of the film density calculated for each step. The radiance of each gray scale step at the time of the photograph was calculated from the radiance of the 36.2% reflectance step measured at the time the photograph was taken and the ratio of the gray scale step reflectances. These calculations gave six radiance vs film density calibration points for each slide.

The calibration data were reviewed by making plots of log radiance vs film density. When plotted this way, the calibration curve is approximately linear in its central portion but becomes strongly curved at each end. If a computer is to be used to process the data, the calibration data must be represented by a nonlinear expression. In general, polynomial fits are not reliable for this purpose because the resulting calibration curves contain unwanted oscillations.

Table I. Gray Scale Calibration Data for Scans in Figures 2 and 3

gray panel radiance[a]	film density	gray panel radiance from polynomial[a]	error[b]
	Photograph from the Near Site		
880	0.191	882	2
578	0.268	575	−3
354	0.437	295	−59
194	0.745	159	−34
88	1.312	103	15
13.7	2.984	30	16
	Photograph from the Far Site		
1141	0.230	1206	65
749	0.313	799	50
459	0.494	431	−28
251	0.799	257	6
114	1.180	192	78
17.7	3.134	36	18

[a] All radiances in the same arbitrary units. [b] Calculated minus measured radiance.

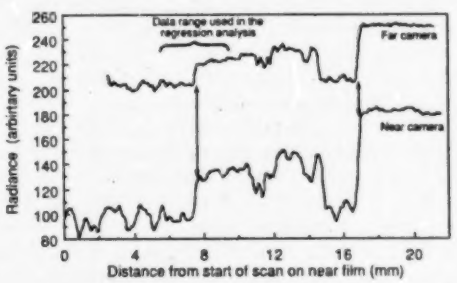
Data range used in the regression analysis
Far camera
Near camera
Radiance (arbitrary units)
Distance from start of scan on near film (mm)

Figure 3. Radiances calculated from the film density scans in Figure 2. The vertical arrows mark points used for registration of the two scans.

The procedure used here was simple and adequate for this demonstration. A fifth degree polynomial was developed that was relatively free of oscillations and described the film characteristics. Then the best values of the first two coefficients (for the constant and linear terms) of the polynomial were determined. The value of the constant depends on the exposure settings used by the automatic camera, and it varied from frame to frame. The linear term is more nearly constant from frame to frame and is related to the contrast (γ) of the film. A table of residuals was calculated for the calibration data from each frame to evaluate the quality of each fit.

Table I shows the quality of fit for data in Figure 2. It is apparent that it would be beneficial to fit the calibration data more carefully than was possible in this exploratory study. Future work should include a more careful derivation of a functional form to describe the film characteristics. Also, it is recommended that the calibration gray scale have more than six steps as, for example, in the work of Larson et al. (*22*).

The film calibration data for each frame were used to calculate a radiance profile from each density scan. Radiance profiles calculated from the film density data in Figure 2 are shown in Figure 3. The data for the abscissa of the upper curve have been adjusted to bring the two profiles into register. This was required because the near

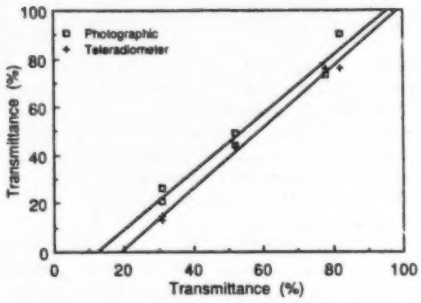

Figure 4. Transmittances measured by the photographic and teleradiometer methods compared to transmittances measured by the rotating target transmissometer. Least-squares regression lines are shown for each measurement method.

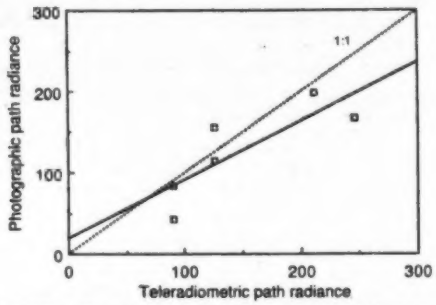

Figure 5. Path radiances in arbitrary units measured photographically compared to path radiances in the same units from teleradiometer readings.

and far images were not exactly the same size and the densitometer scans were not started at exactly the same place in the scene. A linear transformation of the slide position data for the upper scan was used to bring the two points marked by arrows in Figure 3 into register.

Once this registration was accomplished, points on the near and far radiance curves in Figure 3 having the same value of the abscissa correspond to the same elements of the scene. The radiance data from the curve for the near photograph give the initial radiance I_0, and the data from the far photograph give the apparent radiance I. Therefore, eq 1 applies point by point to the two curves in Figure 3 and a linear transformation converts the near radiance curve into the far radiance curve. The best fit parameters for this transformation can be found by a linear regression analysis. The slope from the regression analysis is the transmittance of the sight path between the two camera locations, and the intercept is the path radiance for this sight path. Only the portions of the radiance curves indicated by the bracket were used in the regression analysis, because it was only for this portion of the scene that the sight path from the far camera to the scene passed satisfactorily close to the near camera. The regression analysis of the data in Figure 3 gave a sight path transmittance of 49% and a path radiance of 156 units on the arbitrary radiance scale used for these experiments. Transmittance and path radiance data were obtained from several pairs of photographs in using these procedures.

Figure 4 is a scatter diagram comparing the transmittance data from the photographic method with two other measures of the sight path transmittance. The abscissa of the figure is the sight path transmittance measured by the rotating target method. The upper line in Figure 4 is a least-squares regression line comparing the photographic data to the rotating target transmittance data. The lower line is a least-squares regression line comparing the teleradiometer data to the rotating target transmittance data. The correlation coefficients from each regression were 0.99. The data from the three measurement methods are in general agreement with each other, and the quality of the results is good enough to show that the photographic method has the potential to produce reliable monitoring data. All three of the procedures used to obtain these data were under development, and it is believed that the quality of the agreement between the three methods could be improved by refinement of each of the experimental procedures.

The path radiances determined from the photographs are compared with the path radiances calculated from the teleradiometer readings in Figure 5. The solid line is a least-squares regression line, and the dotted line indicates perfect agreement. Four out of six points show good agreement. It is believed that improved film calibration procedures would significantly improve the accuracy and precision of the path radiances calculated from the photographs.

Discussion

These preliminary data demonstrate that this photographic method of visibility monitoring has the potential to provide useful optical data from simple photographic equipment. The only nonstandard equipment required for this method to be used without operators present is a light meter–timer, which controls the times of the photographs and makes a radiance reading available for recording on the photographic film.

The recording of absolute film calibration data and the time and date on each photographic frame has the following advantages:

1. Automatic exposure cameras can be used to obtain the optimum exposure for each frame, and no records need be kept of the aperture and shutter speed.
2. Any reliable local service can be used for film development, and no special handling or special calibration procedures are required in the photographic laboratory.
3. If the film is subjected to adverse conditions (such as extreme heat) after some but not all of the frames have been exposed, the latent images of the calibration data will be altered in exactly the same way as the latent images of the scene. Distortions of the images by improper film handling and development can be detected and accounted for during data reduction.
4. Recording the time, date, and radiance data on the photograph itself minimizes the dependence on auxiliary records kept on data loggers or in notebooks.

Targets with large areas of relatively uniform reflectance, such as shown in Figure 1, are not necessary. The most important requirement is that the scene in the photographs include both light and dark areas large enough to be resolved both in the photographs and by the densitometer that scans the photographs. In settled areas, buildings, trees, and unforested ground or rocks can give adequate contrast. In remote areas, forested areas, rocks or cliffs, snow patches, etc. can be used.

The sight path from the far camera to the portion of the scene used to obtain film density and radiance data should pass close to the near camera. When this is the case, the radiances measured by the near camera are a good measure of the initial radiances to be used in eq 1 for the sight path between the two camera locations. If the sight paths are not well aligned, they will travel through different portions of the atmosphere between the near camera site and the scene and may view different amounts of sunlit and shadowed portions of the scene. If the surfaces in the scene are rough or uneven, the reflectance can depend quite

strongly on the direction of view. Therefore, it is recommended either that the densitometer scan be made on portions of the scene predominantly made up of smooth, nonglossy surfaces or that care be taken to align the two cameras on the same sight path.

It is preferable to avoid using portions of the scene with fine detail that can be resolved by the photographic film but not by the densitometer. When possible, it is recommended that the focal lengths of the camera lenses be inversely related to the distance to the scene so that the scenic elements will be of the same size in each photograph. When this is the case, any limitations of the resolution of the film or the densitometer will have nearly the same effect on both density scans and will tend to cancel out in the data reduction.

The separation of the camera locations, which determines the length of the sight path, should be selected on the basis of the range of extinction coefficients expected. Rayleigh scattering alone limits the transmittance of a 10-km (6-mi) sight path to 90%, so longer sight paths are seldom required. A path length of 3 km might be appropriate for a polluted urban area because the 10–90% transmittance range corresponds to extinction coefficients between about 35 and 750 Mm^{-1} (0.035 and 0.75 km^{-1}).

It is a significant advantage of this method that the transmittance, path radiance, and initial radiances are determined from the monitoring data. These quantities must be known to characterize the visibility between the two camera locations (5). Also, when these quantities are known, it is possible to calculate the apparent radiance of any element of the scene near the sight path for which the initial radiance and path radiance are known. Therefore, it is possible to calculate the effect of the atmosphere in the sight path on visual parameters, such as modulation and contrast, from these data.

The transmittance and path radiance data reported here are for green light and were obtained from the magenta-forming layer of color slide film. Similar data could be obtained from the cyan- and yellow-forming layers for red and blue light. Also, black-and-white film can be used with color filters on the camera lenses and the light meters. Measurements with photographic film and filter combinations that lead to a response to a broad band of wavelength ranges are not recommended because of the strong wavelength dependence of the transmittance and path radiance of sight paths.

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